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***FUSE* Observations of the Cygnus Loop: O VI Emission from a Nonradiative Shock ¹**

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ABSTRACT

We present *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) observations of a Balmer filament in the northeast region of the Cygnus Loop supernova remnant. The data consist of one spectrum obtained through the $30'' \times 30''$ (LWRS) aperture and three spectra at adjacent positions obtained through the $4'' \times 20''$ (MDRS) aperture. The nonradiative shocks in the region giving rise to these faint optical filaments produce strong O VI $\lambda\lambda 1032, 1038$ emission, which is detected in all the spectra. The O VI emission is resolved by *FUSE* into a strong component centered at 0 km s^{-1} , and weaker components centered at $\pm 140 \text{ km s}^{-1}$. The MDRS spectra allow us to study the variation of O VI emission in the post-shock structure. We find that the zero velocity emission is associated directly with the Balmer filament shock, while the high velocity emission comes from a more uniformly distributed component elsewhere along the line of sight. We also find that the shocks producing the emission at $\pm 140 \text{ km s}^{-1}$ have velocities between 180 km s^{-1} and 220 km s^{-1} , if we assume that the ram pressure driving them is the same as for the zero velocity component shock. In the context of the cavity model for the Cygnus Loop, the interaction of the blast wave with the spherical shell that forms most of the cavity wall can naturally give rise to the similar red and blue-shifted components that are observed.

Subject headings: ISM: individual (Cygnus Loop) — ISM: supernova remnants — shock waves

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1. Introduction

Among the most prominent lines in the ultraviolet spectra of several supernova remnant (SNR) shocks are O VI $\lambda\lambda 1032, 1038$, a doublet with the ground state as their common lower level. O VI is produced in shocks with velocities of at least 160 km s^{-1} . For shocks with velocities up to about 400 km s^{-1} , the strength of the O VI lines is very sensitive to the shock velocity. In addition, the O VI line strength also depends on the column density swept up by the shock. The regions producing O VI emission are typically at temperatures near $300,000 \text{ K}$. Therefore, these lines are the best tracers of SNR gas that is cooler than the x-ray emitting regions, and hotter than the regions of bright optical emission.

The optically faint filaments in the northeast region of the Cygnus Loop SNR produce a large amount of O VI emission. In this region, the optical emission is dominated by Balmer lines, which are collisionally excited in a narrow zone behind the shock front (Chevalier, Kirshner & Raymond 1980). The ultraviolet lines, including O VI $\lambda\lambda 1032, 1038$, come from the hot post-shock gas further downstream where elements are moving to higher stages of ionization. The shocked gas has not had time to recombine and cool radiatively and so these shocks are termed “nonradiative”.

Strong O VI emission was detected in a *Hopkins Ultraviolet Telescope (HUT)* spectrum of a bright nonradiative filament in the northeast Cygnus Loop by Long et al. (1992). They found that the ratio of line strengths I_{1038}/I_{1032} implied significant resonant scattering along the line of sight, and inferred a pre-shock density between 5 and 12 cm^{-3} . However, they also found that the overall *HUT* spectrum was best fit by a 180 km s^{-1} shock running into material with a density of 2 cm^{-3} . Other studies of the same filament based on spectra of the Balmer lines and on *International Ultraviolet Explorer (IUE)* data also suggest that the preshock density is $\sim 2 \text{ cm}^{-3}$ (Raymond et al. 1983; Hester, Raymond & Blair 1994). More recently, analysis of the distribution of C IV $\lambda 1549$ and N V $\lambda 1240$ emission in a region behind the shock front (seen in a spatially resolved *Space Telescope Imaging Spectrograph* spectrum) showed that the pre-shock density is at least 2 cm^{-3} (but probably closer to 4 cm^{-3}), and that the shock velocity is $\sim 180 \text{ km s}^{-1}$ (Sankrit et al. 2000).

Here, we present *Far Ultraviolet Spectroscopic Explorer (FUSE)* observations of a portion of this well studied Balmer filament. The only SNR lines detected in the *FUSE* bandpass are O VI $\lambda\lambda 1032, 1038$. However, in contrast to the *HUT* spectrum, the two lines of the doublet are clearly separated from each other and from the $\text{Ly}\beta$ airglow line, and they are resolved into complex line profiles that vary with spatial position behind the shock.

2. Observations

FUSE observations were obtained on 2000 June 6, as part of the Guaranteed Time Team project on SNRs. The first observation was obtained through the low resolution (LWRS) $30'' \times 30''$ aperture on the filament (centered at $\alpha_{2000} = 20^{\text{h}}56^{\text{m}}06^{\text{s}}.57$, $\delta_{2000} = +31^{\circ}56'05''.6$). Three other observations were obtained through the medium resolution (MDRS) $20'' \times 4''$ aperture with the long dimension parallel to the filament. The first MDRS position was centered on the same location as the LWRS observation, and the next two were obtained with the slit stepped back each time by $\sim 3''$ perpendicular to its length. (Henceforth, we will refer to these positions as P1, P2 and P3.) Details of the observations are presented in Table 1. In Figure 1, the aperture locations are shown overlaid on a WFPC2 $\text{H}\alpha$ image of the filament (Blair et al. 1999).

FUSE has four independent channels, LiF1, LiF2, SiC1, and SiC2, each with two segments, “A” and “B” (see Moos et al. (2000) for details). Four segments, LiF1A, LiF2B, SiC1A, and SiC2B cover the wavelength region $\sim 1000 - 1100\text{\AA}$, which includes the O VI $\lambda\lambda 1032, 1038$ doublet. Of the four segments, LiF1A is the one with the largest effective area at 1035\AA , and the O VI lines are well detected. Furthermore, since the LiF1A channel is used for guiding, only the LiF1 apertures can be held accurately in position for the duration of an observation – other channels drift with respect to LiF1 due to thermal motions (Sahnou et al. 2000). Therefore, in this paper we present only data from the LiF1A segment.

For each observation, we combined the raw data from all individual exposures and then used CALFUSE pipeline version 1.8.7 to produce calibrated spectra. A shift was applied to the flux vectors for each observed LiF1A spectrum in order to line up geocoronal $\text{Ly}\beta$ emission at the appropriate wavelength in the heliocentric frame of reference. (The average geocentric to heliocentric velocity is calculated and included in the headers of the calibrated FITS files.) The pipeline slightly oversubtracts the background, so we added a correction to the flux vectors – this step was done to avoid negative fluxes in the plots; the measured line strengths are not affected.

3. Results

The LWRS spectrum between 1024\AA and 1040\AA is shown in Figure 2. Each O VI line has a strong central component, and emission on both red and blue wings. The wings are prominent in the 1032\AA line but much weaker in the 1038\AA line. The spectral resolution for emission lines from extended sources is the filled slit width $\sim 0.34\text{\AA}$, which corresponds to

$\sim 100 \text{ km s}^{-1}$ at 1034\AA . (This is the width of the airglow lines in the spectrum.) The width of the central component of the O VI emission is about the filled slit width. The integrated line fluxes of the 1032\AA and 1038\AA lines (including the central component and the wings) are $7.67 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ and $3.66 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$, respectively.

The MDRS spectra between 1024\AA and 1040\AA are shown in Figure 3. The filled slit spectral resolution with this aperture is $\sim 0.045\text{\AA}$, which corresponds to $\sim 13 \text{ km s}^{-1}$ at 1034\AA . The O VI lines are broader than the filled slit width (compare the O VI lines with the airglow lines). The two components on the wings of the 1032\AA line are clearly seen in each of the spectra. The O VI line strengths decrease from P1 to P3. Also, in the P3 spectrum, the lines are broader and the central component of O VI $\lambda 1032$ is double peaked. The wing components are about equally strong at all three positions. The O VI line fluxes in the MDRS spectra, along with the fluxes in the LWRs spectrum are given in Table 2. The fluxes were obtained by simple trapezoidal integration over the line profiles. The error in each measurement is dominated by the absolute flux calibration, which is accurate to 10% (Sahnow et al. 2000).

The O VI line fluxes at the three MDRS positions are plotted against velocity in Figure 4. The top panel shows O VI $\lambda 1032$ and the bottom panel shows O VI $\lambda 1038$. The central components of the 1032\AA line and the 1038\AA line are centered at 0 km s^{-1} , and their FWHMs are $\sim 100 \text{ km s}^{-1}$. The components on the 1032\AA line wings are centered at approximately $\pm 140 \text{ km s}^{-1}$.

The intrinsic line profiles of O VI $\lambda 1032$ and O VI $\lambda 1038$ are expected to be identical, except that the 1032\AA line is twice as strong as the 1038\AA line in the optically thin limit. The features on the wings of the 1032\AA line in the *FUSE* spectra are not likely to be spurious since we see them in the LiF2B spectra as well. (The LiF2B spectra are not shown here.) Their absence in the 1038\AA emission can be attributed to absorption by molecular hydrogen along the line of sight between us and the Cygnus Loop. The Lyman band transitions of H_2 , $\text{R}(1)_{5-0}$ and $\text{P}(1)_{5-0}$, have rest wavelengths of 1037.146\AA and 1038.156\AA , respectively (Morton & Dinerstein 1976). Relative to the central O VI wavelength (1037.617\AA) these are at -136 km s^{-1} and $+155 \text{ km s}^{-1}$, respectively. If H_2 is present along the line of sight, then we expect these strong transitions to affect the spectrum strongly around the O VI 1038\AA line.

To check this quantitatively, we used a *FUSE* spectral simulation routine, FSIM, to examine the effects of H_2 absorption. O VI emission components at zero velocity and at $\pm 140 \text{ km s}^{-1}$ were included. The peak fluxes on the 1032\AA wings were chosen to be $4 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{\AA}^{-1}$; the peak fluxes of the 1038\AA line were chosen to be half this value (valid for optically thin line emission). We find that 10^{16} cm^{-2} of H_2 at a temperature of

250 K would be sufficient to absorb the O VI $\lambda 1038$ wings to the point that the emission would be undetectable. Although we do not attempt to set any limits, we conclude that there is sufficient molecular hydrogen towards the Cygnus Loop that results in the O VI $\lambda 1038$ wings being absorbed. (O VI line profiles showing the presence of overlying H₂ absorption are also seen in *FUSE* spectra of other regions in the Cygnus Loop (Blair et al. in preparation).)

4. Discussion

The set of MDRS spectra were obtained in order to map the spatial distribution of the O VI emission perpendicular to the shock front. We find that the central component of O VI emission is well correlated with the H α emission from the filament. The O VI flux is highest at P1, where the filament is most edge-on and the H α is brightest (Figure 1), and is lower at positions P2 and P3, which lie behind the leading edge of the filament. Furthermore, the O VI and H α emission are both centered at 0 km s⁻¹ (Figure 4, and Hester, Raymond & Blair (1994)). The high velocity components, on the other hand, do not vary much among the three MDRS positions (Table 2) and we infer that they come from regions that are more uniformly distributed (in the plane of the sky) than the gas behind the optical filament.

The O VI surface brightnesses measured in the *FUSE* spectra and in the HUT spectrum are listed in Table 3. The HUT observation was obtained with the $9'.4 \times 116''$ placed with its length along the Balmer filament (see Figure 1 of Long et al. (1992)). At the distance of the Cygnus Loop – 440 pc (Blair et al. 1999), the aperture length corresponds to ~ 0.25 pc. The O VI surface brightness of the region observed by HUT is as high as it is at P1. Therefore, we infer that strong O VI emission is more or less uniformly distributed along the length of the filament. Spatial variations in the O VI flux are much larger in the direction perpendicular to the shock front.

Approximately 1/3 the area of the LWRs aperture covers a region that is ahead of the H α filament (Figure 1). Therefore it is not surprising that the O VI surface brightness in the LWRs spectrum is even lower than the surface brightness in the MDRS P3 spectrum. The average surface brightnesses of the three MDRS apertures are 13.5×10^{-16} erg s⁻¹ cm⁻² arcsec⁻² for O VI $\lambda 1032$ and 6.9×10^{-16} erg s⁻¹ cm⁻² arcsec⁻² for O VI $\lambda 1038$. If we assume that 2/3 of the LWRs aperture is filled with O VI, we can calculate corrected LWRs surface brightnesses by multiplying the values in Table 3 by 3/2. The corrected surface brightnesses are 12.8×10^{-16} erg s⁻¹ cm⁻² arcsec⁻² and 6.2×10^{-16} erg s⁻¹ cm⁻² arcsec⁻² for the 1032Å and 1038Å lines, respectively. These numbers are much closer to the average MDRS brightnesses. This analysis suggests that there is very little O VI emitted in the region just ahead of the filament.

By comparing various spectra taken by *FUSE* and HUT, we have inferred some of the properties of the distribution of O VI emission in the vicinity of the Balmer line filament. Now, we consider the properties of the emission components in the MDRS spectra and what can be learned from them about the shock and cloud properties.

4.1. The Zero Velocity Component

The distribution of O VI emission seen in the three MDRS spectra is affected by the history and the geometry of the shock front. According to our current understanding of the Cygnus Loop, based on the the cavity model (Hester, Raymond & Blair 1994; Levenson et al. 1998), the shock now giving rise to the Balmer filaments encountered the cavity “wall” several hundred years ago. Although the radial density profile of this “wall” is not known, it is likely that the pre-shock density was lower and the shock velocity higher at earlier times. The contribution to the O VI flux from these earlier times is uncertain, but probably not very high: a fast shock will ionize oxygen past O⁵⁺ rapidly, and the lower pre-shock density implies a lower O VI yield. Hence it is likely that the differences in the zero velocity component of O VI emission among the three MDRS spectra are due mainly to the shock geometry. In this paper, we will not consider the shock history further.

The shock front is a rippled sheet with a peak to peak amplitude of $\sim 10''$, measured in the WFPC2 H α image of the filament (Blair et al. 1999). On larger scales, the shock front is curved with the convex face outward (Levenson et al. 1998). It may be assumed that the filament similarly curves along the line of sight. The O VI flux is highest at P1 because it is closest to the edge – i.e. it is “limb-brightened”. The flux at position P3 is lower because the path length through the emitting gas is shorter than at P1. Because the path length is shorter, the effects of resonance scattering are smaller and the $I_{\lambda 1038}/I_{\lambda 1032}$ is closer to 0.5 at P3 than at P1 (Table 2). The O VI lines are slightly broader in the P3 spectrum than in the P1 and P2 spectra, and the 1032Å line shows a double peak. This is due to the curvature of the filament – much of the emission at P3 comes from portions of the shock front that have a small radial velocity component.

We have accounted for the spatial variation of the O VI emission seen in the MDRS spectra in a qualitative way using geometric arguments. However, the spatial resolution and coverage of the observations are insufficient to distinguish between different values of the shock velocity and pre-shock density. Therefore, in the following discussion, we use the average O VI surface brightness of the three MDRS positions.

The total flux of the O VI λ 1032 zero velocity component in the MDRS spectra (P1,P2

and P3) is $2.72 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Table 2), which corresponds to a surface brightness of $1.13 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$. In order to compare the observed flux with shock model predictions, two corrections have to be made. First, the interstellar extinction has to be accounted for. We use the extinction curve presented by Fitzpatrick (1999) and find, for color excess $E_{B-V}=0.08$ to the Cygnus Loop (Fesen, Blair, & Kirshner 1982) and $R_V = 3.1$ (the standard ISM value), that the correction factor is 2.8 at 1032\AA . Second, since we are viewing the shock close to edge-on, the resonance scattering of the O VI lines can significantly attenuate their intensities. If resonant scattering effects were very small (i.e. the optical depth in the lines was negligible) then the ratio $I_{\lambda 1038}/I_{\lambda 1032}$ would be 0.5. The observed ratio is about 0.60, which implies that the optical depth in the 1032\AA line is ~ 0.8 . Following the procedure outlined in Long et al. (1992), we find that the attenuation factor for the line is ~ 1.5 . The corrected surface brightness of the central component of O VI $\lambda 1032$ (obtained by multiplying the measured surface brightness by these correction factors derived above) is $4.7 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$.

We choose parameters based on earlier studies of the filament (Raymond et al. 1983; Long et al. 1992; Hester, Raymond & Blair 1994; Sankrit et al. 2000) and use these in shock models to see how the predictions compare with the observation. Three models were calculated, with shock velocities of 170, 180 and 190 km s^{-1} . Diffuse ISM abundances, where O:H = 8.70:12.00 on a logarithmic scale (Cowie & Songaila 1986), and a pre-shock hydrogen number density of 3 cm^{-3} were used in all the models. The models were calculated using an updated version of the code described by Raymond (1979). The models predict the face-on O VI intensity as a function of the swept up column density.

In order to compare the predicted intensity with the observed intensity it is necessary to take into account the viewing aspect ratio, i.e. the ratio of actual shock surface area lying within the slit to the projected area. The observed region is $10'' \times 20''$ (the MDRS positions overlap - see Figure 1). If the extent of the shock front along the line of sight is l arcseconds, then since the MDRS apertures are placed parallel to the filament, the aspect ratio is $\sim l/10$. Figure 1 of Hester, Raymond & Blair (1994) shows that the filament is about $300''$ long. If we assume that the extent of the filament along the line of sight is comparable to its extent on the sky (there is no reason to believe otherwise), then the aspect ratio is about 30. Now, the filament we are studying is the brightest Balmer filament in the northeast Cygnus Loop. This may be a selection effect based on a longer path length along the line of sight so in the following discussion we also consider the possibility of a higher aspect ratio as well.

In Figure 5 the O VI intensities predicted by the shock models are plotted as functions of swept up hydrogen column density. The horizontal lines show the observed intensities (corrected for interstellar extinction and resonance scattering as described above) for aspect

ratios of 30 and 60, which may be considered as approximate bounds on the true value. Note that these models are all calculated for pre-shock density, $n_0 = 3 \text{ cm}^{-3}$; for a given shock velocity and swept up column density, the O VI intensity scales linearly with n_0 . Analyses of other ultraviolet spectra (Long et al. 1992; Sankrit et al. 2000) have shown that the swept up column density lies in the range $\sim 0.8\text{--}2 \times 10^{17} \text{ cm}^{-2}$. From the plot we see that the models predict the O VI emission correctly. The important conclusion of the preceding analysis is that the observed O VI flux can be accounted for by nonradiative shock emission alone – it is not necessary to invoke other mechanisms such as cloud evaporation, or “coronal” emission from cooling gas ionized at an earlier time.

The 180 km s^{-1} shock model predicts a total O VI line intensity ~ 16 times the $\text{H}\alpha$ intensity for a swept up column of $1 \times 10^{17} \text{ cm}^{-2}$. Although only the O VI doublet lines lie in the *FUSE* bandpass, other strong UV lines have been detected in spectra of this filament. Predicted intensities of these UV lines from similar shock models are given by Long et al. (1992). Several lines of He I, He II, O IV and O V at wavelengths below 912\AA are predicted to be comparable to O VI in intensity. The strongest of these are He II $\lambda 304$ (a few times as strong as O VI), and O V $\lambda 630$ (about 1.5 times as strong as O VI). These lines cannot be observed because of interstellar absorption, but they can be important for photoionization of the pre-shock gas (Hamilton & Fesen 1988).

A few lines in the optical range are expected to be present at the level of a few percent the brightness of $\text{H}\alpha$, in particular He I $\lambda 6678$, He II $\lambda 4686$ (Hartigan 1999) and [O III] $\lambda 5007$. The brightest predicted line, [Ne V] $\lambda 3425$ at about 10% the $\text{H}\alpha$ intensity, was detected by Raymond et al. (1983). Infrared emission lines are predicted to be very faint, the brightest being [O IV] $25.9\mu\text{m}$ and [Ne VI] $7.6\mu\text{m}$ lines at about 1% the intensity of $\text{H}\alpha$.

4.2. The Wing Components

The total flux of the high velocity O VI at the three MDRS positions is $5.3 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Table 2). The correction for interstellar extinction is exactly the same as for the main component (a factor of 2.8). As we discuss below, resonance scattering effects may be neglected. So, the corrected surface brightness for the wing components (red and blue total) is $6.2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$. It is seen from Figure 4 that flux in the blue wing is approximately the same as the flux in the red wing. To check this quantitatively, we fit gaussians to the wing profiles, and also evaluated the integrals under the curve, between suitably chosen points. Both methods showed that the difference in flux between the two wings is $\lesssim 10\%$. For the following discussion, we assume that the two components are equally bright and consider only the blue wing – the arguments used and results derived apply equally

well to both components.

We start by making the assumption that the -140 km s^{-1} emission is due to a steady shock traveling towards us, and that we are looking through just a single shock structure. (The line optical depth will be small, and attenuation of the flux due to resonance scattering can be neglected.) The angle between the shock normal and the line of sight (θ), the observed and face-on surface brightnesses, and the observed velocity and shock velocity are related by

$$\cos\theta = \frac{v_{obs}}{v_s} = \frac{I_0}{I_{obs}} \quad (1)$$

and the latter relation may be written as

$$I_0 v_s = I_{obs} v_{obs}. \quad (2)$$

Thus, there are a family of solutions for the shock velocity and face-on surface brightness that will match the observations.

We next assume that the pressure driving this shock is equal to the pressure driving the shock responsible for the $\text{H}\alpha$ filament and the zero velocity O VI emission. This is a reasonable assumption since ROSAT x-ray maps show no evidence for large pressure variations in the region (Levenson et al. 1997). Then the isobaric relation, $n_0 v_s^2 = \text{constant}$, holds. The constant, based on the parameters used in the model described above (§4.1), is $3 \times 180^2 = 97200 \text{ (cm}^{-3}\text{)(km s}^{-1}\text{)}$. The isobaric relation can be used to specify the pre-shock density for every assumed value of shock velocity.

As discussed in §4.1, for a given shock velocity and pre-shock density, the O VI intensity depends on the swept up column density. A third constraint on the shock parameters is obtained from the relation

$$n_0 v_s t_{shock} = N_H. \quad (3)$$

Here t_{shock} is the time since the shock interaction started (the age of the shock), and N_H is the swept up column density.

We ran a sequence of models with shock velocities $160 - 300 \text{ km s}^{-1}$. The pre-shock densities were calculated using the isobaric condition. Equation 2 was used to find the required O VI surface brightness for each shock velocity. For each model this was achieved at some value of the swept up column density. (The exception is the 160 km s^{-1} shock, which does not produce enough O VI emission to match the observations.) The age of the shock is then found from equation 3. In Table 4 we list the parameters used in the models, the required O VI 1032Å surface brightnesses, and the resulting swept up column density and shock age. The swept up column density required to produce the observed O VI increases with shock velocity. As a consequence of the isobaric condition and equation 3,

$t_{shock} \propto N_H v_s$, so the shock age also increases with shock velocity. There is a sudden jump in the required N_H , and hence the shock age between shock velocities 200 and 220 km s⁻¹. This is because in faster shocks, the oxygen rapidly ionizes to O⁶⁺ and beyond and the required O VI intensity is produced only after the gas recombines to O⁵⁺.

The age of the Cygnus Loop is $\sim 9,000 \times (D_{pc}/440)$ yr, where D_{pc} is the distance to the remnant (Levenson et al. 1998). Since the shock age cannot exceed the age of the remnant, shock velocities $\gtrsim 260$ km s⁻¹ are ruled out (Table 4). However, more stringent limits can be placed on the shock velocity because detailed studies of the northeast Cygnus Loop (Hester, Raymond & Blair 1994) show that the interaction started ~ 1000 yr ago. Therefore, the allowed range of shock velocities is 180–220 km s⁻¹ (Table 4). The angles between the line of sight and the shock normal for the lower and upper velocity limits are 39° and 50°, respectively (equation 1).

We note that the exact upper limit on the shock velocity derived above depends on the value of the constant in the isobaric relation. It also depends upon the observed O VI surface brightness, for which the error is dominated by the uncertainty in our knowledge of the reddening correction at 1032Å. However, the expected range of values for these parameters is sufficiently narrow that though the limit may be revised upward by some tens of km s⁻¹, the basic picture for the production of O VI emission would not change.

Our analysis has shown that either high velocity component of O VI can be produced by a shock with properties similar to the one producing the Balmer line emission. The similarity between the blue and red wing components (equal flux, symmetric about zero in velocity space) can be understood in the context of the cavity model for the Cygnus Loop. In this model (Hester, Raymond & Blair 1994; Levenson et al. 1998), the blast wave is interacting with the walls of the cavity cleared by the progenitor star. According to the picture presented by Levenson et al. (1998), the cavity wall consists of a neutral atomic shell covering most of the surface, and several large cloud boundaries filling in the rest. The shell was formed by recombination at the edges of the pre-supernova H II region. In such a model we expect to see symmetrical red- and blue-shifted shocks along lines of sight that do not intersect the large clouds. Thus, in the high velocity wings observed with *FUSE* we are seeing the shock wave interacting with the neutral shell. Because the shell is spherically symmetric, our line of sight will pass through shock fronts inclined at equal angles toward us and away from us.

5. Concluding Remarks

We have detected strong O VI emission from a Balmer filament in the Cygnus Loop. The *FUSE* data presented here have the spectral resolution not only to separate the two O VI lines from each other and from the Ly β airglow, but also to separate kinematically different emission components along the line of sight. The O VI flux distribution, sampled at a spatial resolution of $\sim 4''$, is correlated with the H α emission. A nonradiative shock with properties derived from other ultraviolet observations can produce the observed O VI. We have also resolved the O VI emission in the form of wings on the main component. These high velocity emission components are centered symmetrically in velocity space, at $\pm 140 \text{ km s}^{-1}$, and have equal flux. They probably arise in shocks driven into the spherically symmetric neutral shell, which, in some cavity models, has a large covering factor around the surface of the remnant.

O VI $\lambda\lambda 1032, 1038$ emission is an important channel through which the Cygnus Loop SNR loses energy. Measurements of the global O VI emission have been obtained using *Voyager 1* and *2* (Blair et al. 1991a; Vancura et al. 1993), and a rocket-borne experiment (Rasmussen & Martin 1992). These studies show that the O VI luminosity is about the same as the luminosity in the 0.1–4.0 keV x-ray band, the latter based on *Einstein* observations (Ku et al. 1984). The contribution of nonradiative shocks to the total O VI emission may be estimated based on our results. The face-on surface brightness of the shock causing the observed wing emission is $\sim 3 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ (total of 1032Å and 1038Å lines). Assuming a covering factor of 50% for such shocks, and distance to the Cygnus Loop of 440 pc, the derived O VI luminosity is $\sim 1.2 \times 10^{36} \text{ erg s}^{-1}$. While radiative shocks are known to contribute to the total O VI emission (Blair et al. 1991b; Danforth, Blair & Raymond 2001), nonradiative shocks could account for most of the total O VI emitted by the Cygnus Loop. The study of O VI emission is clearly important for unraveling the details of the interaction between the Cygnus Loop and the surrounding material, and by extension for understanding the nature of other middle-aged cavity SNRs.

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Fig. 1.— Aperture locations overlaid on a WFPC2 $H\alpha$ image of the Balmer filament in the Cygnus Loop. The large box (dashed line) represents the $30'' \times 30''$ LWRS aperture and the smaller boxes represent the $4'' \times 20''$ MDRS aperture. The shock direction is shown on the image.

Fig. 2.— LWRS spectrum of the filament showing the region around the O VI $\lambda\lambda 1032, 1038$ lines. The line at about 1025.8\AA is $\text{Ly}\beta$, and the other airglow lines are from O I. The feature on the blue wing of the $\text{Ly}\beta$ is a detector artifact.

Fig. 3.— MDRS spectra showing the region around the O VI lines. Position 1 refers to the aperture location that is furthest ahead, on the optical filament (Figure 1). Positions 2 and 3 are stepped back perpendicular to the shock normal. All spectra have been binned by 4 pixels. Airglow lines are marked on the Position 1 spectrum.

Fig. 4.— O VI line fluxes plotted as a function of velocity for the three spectra. The top panel shows the 1032\AA line and the bottom panel shows the 1038\AA line. The scales are the same on both plots so they can be compared easily. The units of F_λ are $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$. In the bottom panel, the positions of a pair of H_2 Lyman band transitions are shown. These H_2 transitions are responsible for absorbing the O VI $\lambda 1038$ wing emission.

Fig. 5.— The cumulative face-on O VI $\lambda 1032$ intensities predicted by shock models plotted versus swept up hydrogen column density. Predictions from three models, with shock velocities of 170, 180 and 190 km s^{-1} are shown. All models use a pre-shock hydrogen number density of 3 cm^{-3} . The intensity for a given shock velocity and swept up column scales linearly with the pre-shock density. The horizontal lines show the observed intensity divided by 30 and 60, to account for the viewing aspect ratio of the shock front. Intensity units are: $10^{-16} \text{ erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$.

Table 1. List of Observations

Obs. ID	α_{J2000}	δ_{J2000}	t_{exp} (s)	Aperture
P1140401	20 ^h 56 ^m 06 ^s .57	+31° 56′ 05″.6	10234	LWRS
P1140402	20 ^h 56 ^m 06 ^s .57	+31° 56′ 05″.6	9559	MDRS (P1)
P1140501	20 ^h 56 ^m 06 ^s .40	+31° 56′ 03″.5	9247	MDRS (P2)
P1140601	20 ^h 56 ^m 06 ^s .23	+31° 56′ 01″.4	9767	MDRS (P3)

Note. — The slit position angle was 308°5 (E of N) for all observations.

Table 2. Observed Fluxes and Flux Ratios

Component	MDRS P1	MDRS P2	MDRS P3	LWRS
1032Å total	1.37	1.12	0.76	7.67
1032Å center	1.22	0.95	0.55	...
1038Å ^a	0.79	0.54	0.31	3.66
1032Å wings ^b	0.15	0.17	0.21	...
$I_{1038}/I_{1032(center)}$	0.65	0.57	0.56	0.48 ^c

Note. — Flux units: 10^{-13} erg s⁻¹ cm⁻².

^aThe central component dominates, as the wings are absorbed by interstellar H₂ lines.

^bThis is simply the difference between the total and center fluxes given in the first two rows.

^cThe components have not been deconvolved in the LWRS spectrum so the ratio $I_{1038}/I_{1032(total)}$ is tabulated.

Table 3. Observed Surface Brightnesses

Component	MDRS P1	MDRS P2	MDRS P3	LWRS	HUT ^a
1032Å total	17.1	14.0	9.5	8.5	16.8
1038Å	9.9	6.8	3.9	4.1	10.1 ^b

Note. — Surface Brightness units: 10^{-16} erg s⁻¹ cm⁻² arcsec⁻².

^aData from Long et al. (1992). The HUT aperture was $9''.4 \times 116''$.

^bLong et al. (1992) reported the total flux in both lines of the doublet. The best fit to their spectrum yielded a ratio $I_{1038}/I_{1032}=0.6$, which we use here.

Table 4. Model Parameters and Results

v_s (km s ⁻¹)	n_0 (cm ⁻³)	I_0^a	N_H (cm ⁻²)	t_{shock} (years)
160	3.80	2.71
180	3.00	2.41	1.86×10^{17}	110
200	2.43	2.17	2.21×10^{17}	140
220	2.01	1.97	1.52×10^{18}	1090
240	1.69	1.81	5.65×10^{18}	4420
260	1.44	1.67	1.26×10^{19}	10650
280	1.24	1.55	2.18×10^{19}	19890
300	1.08	1.45	3.29×10^{19}	32140

^aUnits are 10^{-16} erg s⁻¹ cm⁻² arcsec⁻².









